MODELLING OF WATER SPRAY COOLING. IMPACT ON THERMOMECHANICS OF SOLID SHELL AND AUTOMATIC MONITORING TO KEEP METALLURGICAL LENGTH CONSTANT

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Abstract

The paper focuses on two points related to water spray cooling during secondary cooling. The first one is the impact in terms of local stress generated along the surface and subsurface of the cast product when passing by each water spray sprinkler. The second point deals with an automatic determination of the water flow rate to be imposed to each sprinkler in view of an increase of the casting speed under the constraint that the metallurgical length should be maintained constant. The 3D finite element software THERCAST® is used to address those two questions.

Keywords

Thermomechanical modelling, thermal stress, water spray, 3D finite element, process control

1. Introduction

Water spray cooling in steel continuous casting represents the second stage for solidification and its modelling is essential to a deep understanding of temperature fields and thermal stresses along the casting process. After the product exits the copper mould, most of it is still liquid and contained in a thin solid shell formed during this primary cooling. It is then extracted by both gravity and motorized rolls through a series of supporting rolls stands and water sprays. During this secondary cooling it undergoes large temperature fluctuations, especially near its surface, that it is essential to understand and control in view of minimizing the occurrence of defects such as surface or sub-surface cracking [1]. These fluctuations arise due to localized sprinkling. Indeed, the surface is cooled down when being exposed to a spray zone, or when in contact with a support roll. Then, it is re-heated when exposed to convection and radiation with air, due to heat conduction from the hotter core. These high temperature gradients induce localized stresses that might give rise to damage. Analysis of spray cooling in CC through numerical simulation should give access to an estimation of those thermal fluctuations and associated stresses. Thereby, this work addresses the study of such cooling phenomena using as computational platform the software THERCAST® which has been specially developed to model solidification processes [2] [3] with special focus on steel continuous casting [4] [5] [6]. The modelling of the cooling is done through the computation of a heat transfer coefficient, which is a complex task due to the formation of a steam layer (Leidenfrost effect). Several models have been proposed in the literature to express the heat transfer coefficient as a function of the local surface water flow rate. They are briefly discussed in Section 2. Such models take into account the water flow rate and the temperature

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difference between water and metal surface. In addition, the spatial dependency of this heat transfer coefficient within a sprayed area is introduced by means of a mathematical distribution function – parabolic or Gaussian – which is used to deduce the local surface water flow rate in a sprinkled area from the global flow rate of the sprinkler.

After having implemented these characteristics in THERCAST® software, numerical simulations are performed to study the influence of water spray cooling patterns on the thermal and mechanical state of cast billets. This is exposed in Section 3.

Finally, in Section 4, the question of process control is addressed. Starting from a nominal water cooling strategy, an algorithm has been developed to automatically determine the water flow rate to be imposed to each spray in view of an increase of the casting speed under the constraint that the metallurgical length should be maintained constant.

2. Heat transfer associated with water spray sprinklers

Spray cooling for high surface temperature, like in continuous casting is complex because the water-metal interaction is perturbed by the formation of a steam layer. In this study, the determination of a local heat transfer coefficient is carried out in two steps. First, the determination of the local distribution of water flow rate V_s [l $m^{-2}s^{-1}$] delivered by each sprinkler in its region of interest. Second, the determination of the local heat transfer coefficient by correlation formula issued from the literature.

Water distribution in a sprinkled region

Water is distributed non-uniformly along the area exposed to sprinkling ("wet area"). The surface flow rate V_s varies radially from the centre up to the border of the area. It depends on a distribution function f which is often chosen as Gaussian or parabolic, depending on the sprinkler type:

$$V_s = f(x,y)\frac{\dot{V}}{A_s} \tag{1}$$

In this equation, $\dot{V}$ [l/s] is the total flow rate delivered by the sprinkler, A_s is the wet area. It depends on the sprinkling cone geometry and on the distance to the product surface. The distribution f is a function of x and y, the coordinates along the sprinkled surface. Its integral over the surface is unitary.

Heat transfer coefficient

For water spray cooling, it is known that the main parameters are the difference ΔT between the surface temperature T_s and the water temperature T_w as well as the surface water flow rate V_s. However, the complexity of the heat transfer phenomena at high temperature comes from the presence of a vapour film due to rapid vaporization of drops impacting the hot surface. This creates a complex interface metal/steam/water with possible decrease of heat transfer due to this steam layer, for ΔT below the Leidenfrost point [7] [8] [9]. The expression obtained by Viscorova in [10] has come up through inverse analysis of experimental data [7]. It gives the convective heat transfer coefficient α, as a function of V_s and ΔT. For V_s varying from 3 to 30 l m^{-2} s^{-1} and ΔT from 150 to 1100 K, α [W m^{-2} K^{-1}] is expressed as:

$$\alpha = 190 + \tanh\left(\frac{V_s}{8}\right)\left(140V_s\left(1-\frac{V_s\Delta T}{72000}\right)+3.26\Delta T^2\left(1-\tanh\left(\frac{\Delta T}{128}\right)\right)\right) \qquad (2)$$

Other expressions can be found in the literature, like the one of Shimada (often – and probably abusively – attributed to Nozaki) or the one of Jeschar. They are not detailed here: see reference [11] in which a quantitative comparison shows similar results in the context of continuous casting. In the sequel, the expression given in Eq. (2) is used.

3. Application to billet continuous casting

After integration of water spray modelling in THERCAST® software, continuous casting of billets of square section is considered.

The product has a square section 85 x 85 mm. The mould length is 0.5 m. The casting temperature is 1500 °C, that is 40 °C over the liquidus temperature, the solidus being 1300 °C. Other material and process data can be found in [11].

Simulations are performed using a symmetry plane throughout the machine, see Figure 1. The non steady-state slice method is used, because by comparison with the global non-steady (GNS) approach, it permits the use a finer mesh, which is important in the present case to discuss short range interactions such as the sudden cooling and reheating undergone by the surface of the product when passing by water sprays.

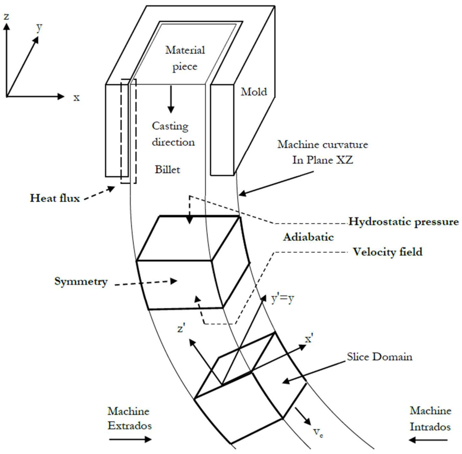

Figure 1: Square billet continuous casting. Boundary conditions associated with the slice approach.

The slice approach consists in conveying throughout the machine a part of the product having a certain length in the casting direction. The computation is defined with particular boundary conditions, please refer to Figure 1. Regarding heat transfer, top and bottom surface are adiabatic, heat is extracted by lateral surfaces only. This approach has been shown to be appropriate in the case of smooth and regular boundary conditions (that is when heat transfer coefficients vary slowly in the casting direction) [4]. In the present context, it is more questionable because when the slice enters or leaves a sprinkled area, there are actually significant temperature gradient axial components which form in the 10 mm thick subsurface region. This point has to be cleared; in the present study we have considered that the slice method, as described above, could still be applied. The mechanical boundary conditions that are considered here are as follows. The casting velocity vector is imposed along the bottom face of the slice, whereas along the upper face a normal stress equal to the metallostatic pressure (continuously increasing with the distance to meniscus) is applied. Lateral faces are considered as mechanical free surfaces, unless when in contact with support rolls, the non-penetration being then treated using a penalty technique. As the slice represented in the global reference frame (x,y,z) rotates due to the machine curvature, a local reference frame (x',y',z') is defined attached to the local position in the machine.

The effective slice geometry and the mesh used can be seen in Figure 2. A hybrid tetrahedral mesh is used in which the mesh size is 1.25 mm up to 15 mm deep under the surface (that is in the region potentially affected by temperature fluctuations). The core of the product has a coarser mesh size of 5 mm.

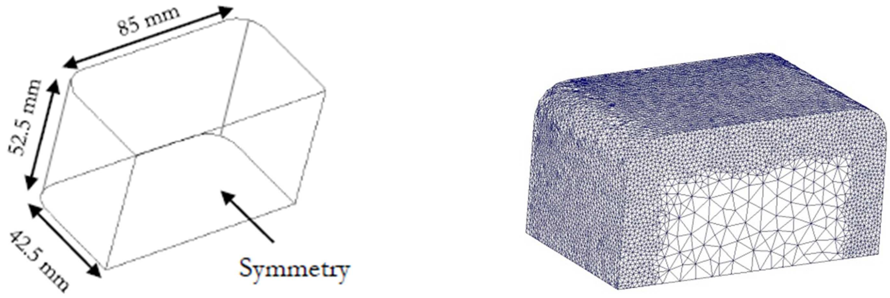

Figure 2: Slice geometry and finite element mesh.

Sprays and rolls positions are defined all along the casting line. Spray flow rate and characteristics (sprinkling angle) are defined as well. The heat transfer coefficient associated with roll contact is constant and equal 2500 W/m^2/K. Figure 3 shows the evolution of the surface temperature at a virtual sensor placed near the surface of the analyzed slice. Temperature is plotted vs the distance of the sensor to the meniscus. It can be noted that results obtained with three different expressions of the local heat transfer coefficient α as a function of V_s (including Eq. (2)) are found very close.

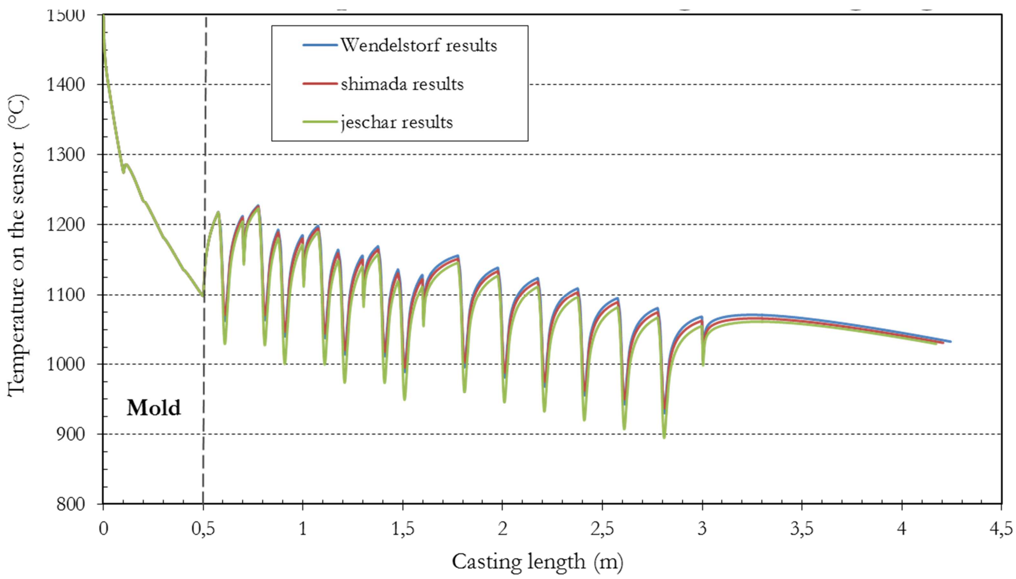

Figure 3: Surface temperature vs distance to meniscus. Results obtained with three different expressions of the local heat transfer coefficient.

The evolution of surface stresses is expected to reflect the thermal response, since they are a consequence of thermal dilatation. Like for temperature analysis, Figure 4 shows the evolution of the equivalent von Mises stress along the casting length. The plot shows large and rapid fluctuations along the casting line, even larger than the thermal ones. Contrary to the thermal peaks, both values and amplitude of stress peaks increase with casting length. This is because the solid steel shell is more and more stiff and thick along with the casting line.

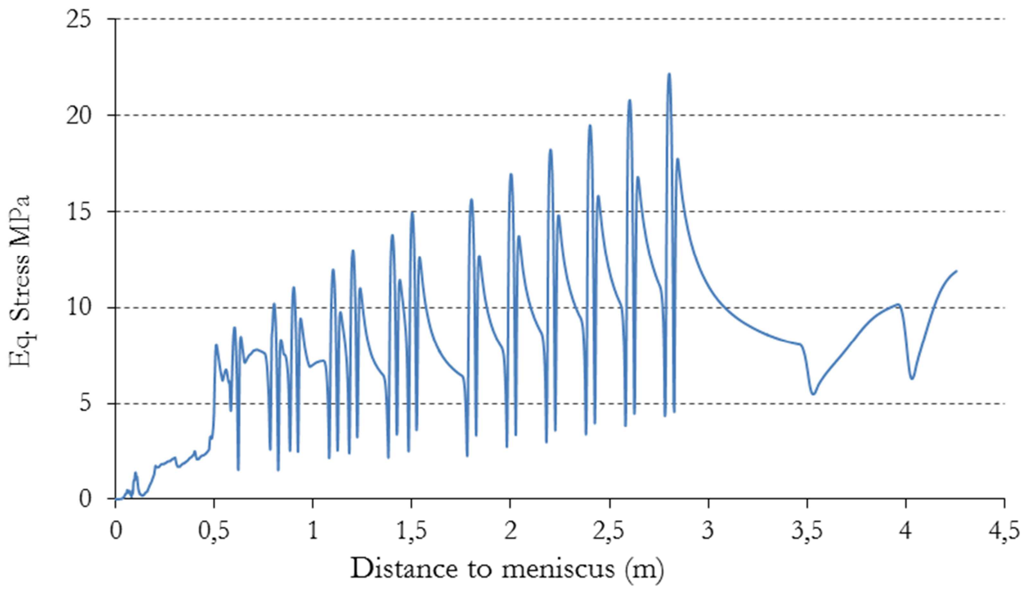

Figure 4: von Mises stress at product surface vs distance to meniscus (V_C = 25 mm/s).

4. Control of water spray cooling

The following problem is then addressed. Let's consider a nominal casting speed V_{C1}, resulting in a certain "metallurgical length": the distance to the meniscus at which the product solidification is completed. This distance can be estimated by use of numerical simulation code such as THERCAST® for instance. The problem we would like to solve is the following: given an increased casting speed, $V_{C2} > V_{C1}$, what should be the new value of water flow rate for each sprinkler to maintain the metallurgical length unchanged?

<u>Approach</u>

To solve this problem, it is assumed that in each of the successive segments of the casting line, defined as the regions of influence of the different spray cooling sets, the decrease of the average energy through a transverse section of the product should be the same for V_{C2} and for V_{C1}. Let's denote **Ω** the domain occupied by the cast product in such a segment of the casting machine. Considering steady-state continuous casting, we have, from energy conservation:

$$\int_{\Omega} \nabla H \cdot \mathbf{v} \mathrm{d}V = \int_{\Omega} \nabla \cdot (k \nabla T) \mathrm{d}V = \int_{\partial\Omega} k \nabla T \cdot \mathbf{n} \mathrm{d}S \tag{3}$$

where H is the volumetric enthalpy, k the thermal conductivity and $\mathbf{n}$ the outward unit vector to the surface. Denoting q [W m^{-2}] the extracted surface heat flux, by means of water spraying, roll contact or convection-radiation with air, we have:

$$\int_{\Omega} \nabla H \cdot \mathbf{v} \mathrm{d}V = -\int_{\partial\Omega} (q_{sprays} + q_{rolls} + q_{air}) \mathrm{d}S \tag{4}$$

We make the assumption that the left hand side can be reasonably approached by the following expression:

$$\int_{\Omega} \nabla H \cdot \mathbf{v} \mathrm{d}V = \int_{\Omega} (\nabla H \cdot \mathbf{e}_{x'}) \|\mathbf{V}_{\mathrm{C}}\| \mathrm{d}V \tag{5}$$

which means that only axial gradients of the enthalpy are considered in the integral, the velocity of the material being very close to the casting speed V_{C}. Thus, we can write:

$$V_{\mathrm{C}} \int_{\Omega} -\nabla H \cdot \mathbf{e}_{x'} \mathrm{d}V = \int_{\partial\Omega} (q_{sprays} + q_{rolls} + q_{air}) \mathrm{d}S \tag{6}$$

The basic idea of the adaptation algorithm proposed here is that the integral appearing on the left hand side – which can be interpreted as the averaged decrease of energy per unit length in the casting direction – should be kept identical all along the machine to result in an unchanged metallurgical length. This leads to the following relation, to be satisfied in any domain Ω along the casting line:

$$\int_{\partial\Omega} q^2_{sprays} \mathrm{d}S = \int_{\partial\Omega} q^1_{sprays} \mathrm{d}S + (V_{\mathrm{C}2} - V_{C1}) \int_{\Omega} -\nabla H \cdot \mathbf{e}_{x'} \mathrm{d}V \tag{7}$$

in which q^1_{sprays} denotes the surface heat flux extracted by sprays in case 1 and q^2_{sprays} is the corresponding quantity we would like to determine for case 2.

Thus, the solution algorithm can be easily deduced from Eq. (7) and is briefly summarized hereafter.

For each segment associated with a spray stand, and on the basis of the numerical simulation corresponding to case 1,

- Calculate the averaged decrease of energy per unit of length in the casting direction;
- Deduce the aimed average surface heat flux q^2_{sprays} from Eq. (7);
- Estimate an aimed average heat transfer coefficient α^2 by the following expression:

$$\overline{\alpha}^2 = \frac{q^2_{sprays}}{\int_{\partial\Omega_{spray}} (T - T_w) \mathrm{d}S} \tag{8}$$

- Using Eq. (1) deduce, by a non-linear resolution, the average water surface flow rate $\overline{V}_s^2$ and finally the adapted flow rate for case 2 for the considered sprinkler set: $\dot{V}^2 = \overline{V}_s^2 A_s$.

<u>Results</u>

We consider billet continuous casting for which the nominal casting speed is V_{C1} = 25 mm/s. Three different casting speeds V_{C2} are envisaged: V_{C2} =23.75 mm/s (-5%), V_{C2} =27.5 mm/s (+10%), and V_{C2} =28.5 mm/s (+14%).

Figure 5 shows the results obtained after application of the algorithm described above. The dashed lines in red and purple represent the cooling profile which would be obtained without any modification of the flow rate of the sprays. It can be seen that increasing the casting speed by 14% results in an increase of the metallurgical length by 0.5 m (+12%). After application of the control algorithm, the metallurgical length varies only by 0.15 m (+3.5%). Considering an increase or a decrease of the casting speed, the metallurgical length is kept within a very narrow range of 0.25 m, that is plus or minus 3% with respect to the nominal metallurgical length. This result shows the relevance of the simple idea consisting in extracting the same energy all along the casting line for the different casting speeds and validates the efficiency of the method to monitor water spray cooling.

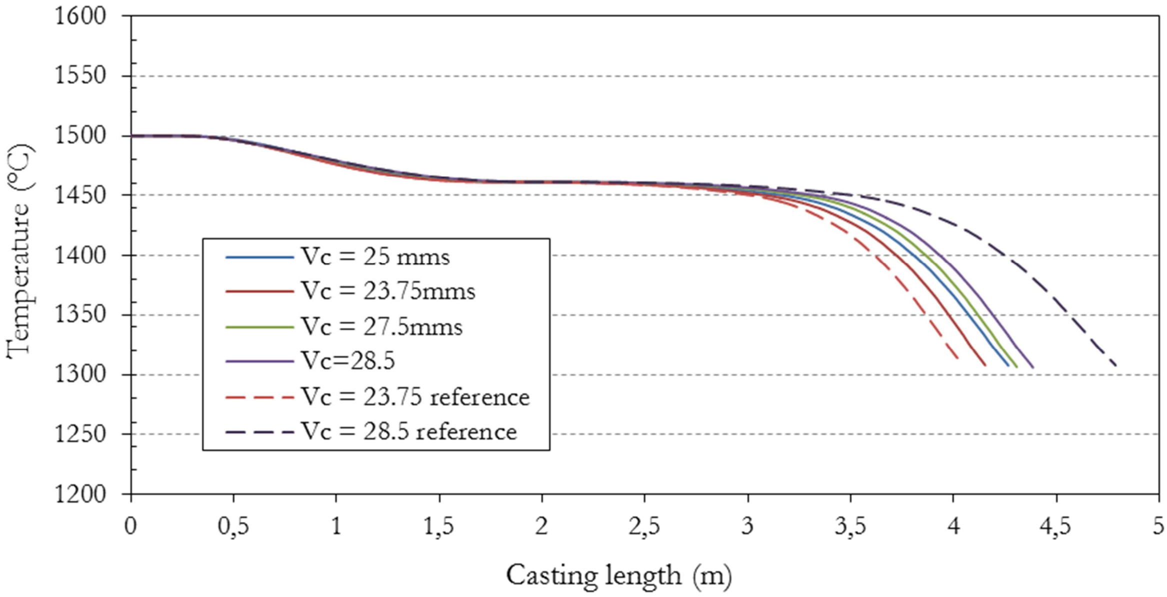

Figure 5: Evolution of core temperature as a function of the distance to meniscus for the different casting velocities. The continuous blue curve for V_C = 25 mm/s serves as a reference. Dashed curves are obtained without control algorithm. Other continuous curves are obtained using the proposed control algorithm.

Figure 6 presents the surface temperature evolution for the different casting speeds when using the algorithm to control the intensity of spray cooling. Around the blue curve, associated with the nominal regime, it can be seen that a decrease in casting speed leads to higher surface temperatures and lower temperature variations along the casting line. Conversely, an increase of V_C leads to lower surface temperatures and a higher amplitude of temperature variations (almost doubled).

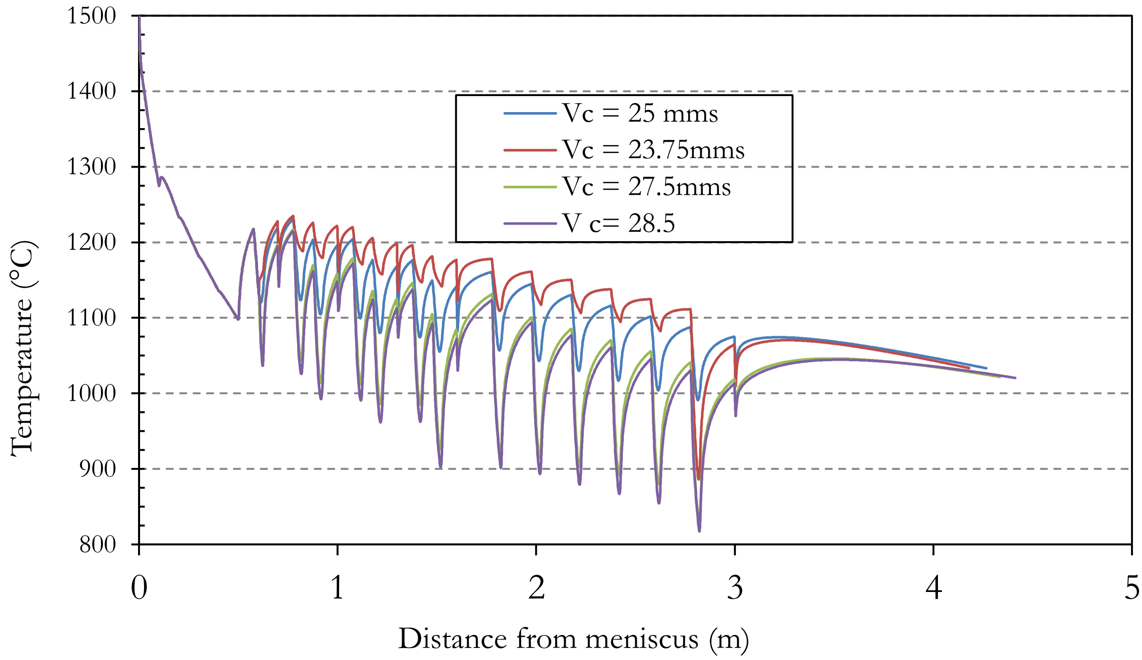

Figure 6: Surface temperature evolution for the different casting speeds when using water spray control.

It has been checked that because of heat diffusion those temperature fluctuations only affects 12 to 15 mm maximum of the product in the thickness direction. However, it is interesting to study the associated stress variations at the surface of the product. Figure 7 shows how the von Mises stress evolves at the surface of the product when passing by sprays and rolls, as a consequence of temperature variations. It can be seen that the peak stress levels are more than doubled, with much higher amplitude of fluctuations for a speed increased by 14%. This is an important phenomenon that may give birth to surface damage.

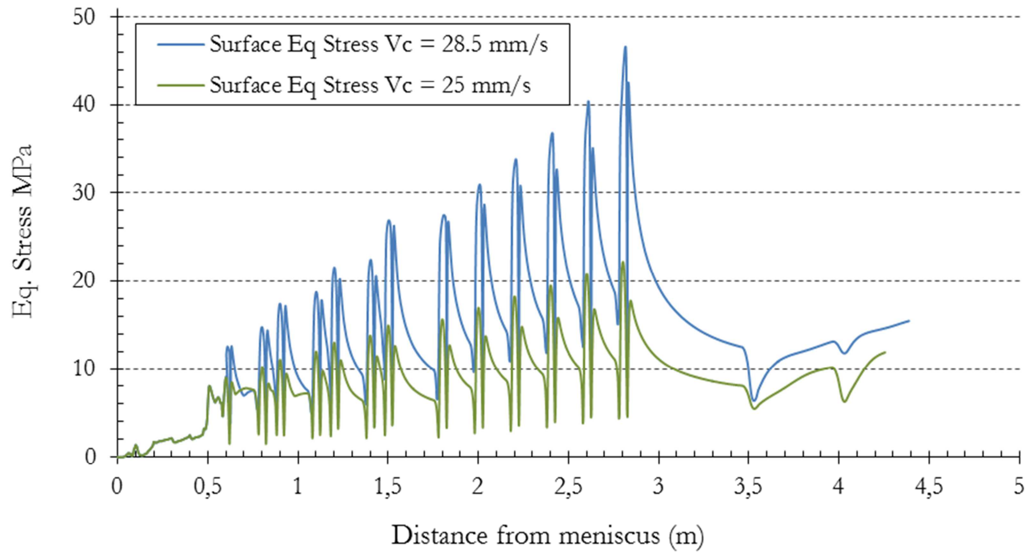

Figure 7: Profile of von Mises stress at the surface of the product along the distance to meniscus, for two casting speeds 25 and 28.5 mm/s.

5. Conclusion

In this paper, water spray modelling has been presented with a special focus on the consequences in terms of surface temperature and stress fluctuations. A 3D finite element analysis has been developed in the context of billet continuous casting, using THERCAST® software. The thermal stresses which affect the surface and subsurface of the product have been found increasing, both in peak values and amplitude of variation, all along the casting line. Regarding the issue of the adaptation water spray intensity to a change in the casting speed, a simple algorithm based on energy extraction has been proposed and implemented. It has been demonstrated that it can provide a good response, the metallurgical length being almost unchanged for an increase or a decrease of the casting velocity with respect to a reference value. An additional result deals with the evolution of thermal stresses generated along the surface and subsurface of the product when proceeding to such changes in water spraying intensity. The analysis reveals that the response is highly non-linear, the increase of stress peak levels and amplitudes being significantly higher than the increase in casting speed.

References

[1] B.G. Thomas, Continuous casting of steel, in Modeling for Casting and Solidification Processing, O. Yu (ed.), Marcel Dekker, New York (2001) 499-540.

[2] M. Bellet, V.D. Fachinotti, ALE method for solidification modelling, Comput. Meth. Appl. Mech. Eng. 193 (2004) 4355-4381

[3] M. Bellet, O. Jaouen, I. Poitrault, An ALE-FEM approach to the thermomechanics of solidification processes with application to the prediction of pipe shrinkage, Int. J. Num. Meth. Heat Fluid Flow 15 (2005) 120-142
[4] M. Bellet, A. Heinrich, A two-dimensional finite element thermomechanical approach to a global stress-strain analysis of steel continuous casting, ISIJ International 44 (2004) 1686-1695
[5] F.Costes, Modélisation thermomécanique tridimensionnelle par éléments finis de la coulée continue d'aciers, Ph.D. Thesis, Ecole des Mines de Paris (2004)
[6] R. Forestier, F. Costes, O. Jaouen, M. Bellet, Finite element thermomechanical simulation of steel continuous casting, Proc. MCWASP XII, 12th Int. Conf. on Modeling of Casting, Welding and Advanced Solidification Processes, Vancouver & Alaska, June 7-13, 2009, S. Cockcroft, D. Maijer (eds.), The Minerals, Metals & Materials Society, Warrendale, Pennsylvania, USA (2009) 295-302.
[7] J. Wendelstorf, K.H. Spitzer, R. Wendelstorf, Spray water cooling heat transfer at high temperatures and liquid mass fluxes, Int. J. Heat Mass Transfer 51 (2008) 4902-4910
[8] J. Wendelstorf, R. Wendelstorf, K.H. Spitzer, Spray cooling heat transfer and calculation of water impact density for cooling of steel sheet materials by inverse process modelling, Steel research 80 (2009) 639-644.
[9] K. Wuennenberg, H. Jacobi, G. Kaestle, Heat transfer in cyclic secondary cooling during solidification of steel, Ironmaking and Steelmaking 11 (1984) 132-145
[10] R. Viscorova, Untersuchung des Wärmeübergangs bei der Spritzwasserkühlung unter Berücksichtigung des Einflusses der Verzunderung, Ph.D. Thesis, Technische Universität Clausthal (2007)
[11] L.F. Salazar Betancourt, Numerical Modeling of the Heat Transfer by Sprinkler Sprays in Continuous Steel Casting, Master Thesis, MaPMod, CEMEF, Mines ParisTech (2013).